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Abstract
An analytical and experimental study is conducted to determine criticality of interlaminar disbands by NDE methods. Criticality of such flaws in a shear environment (action of shear near support) is defined in terms of crack propagation and is analyzed by principles and methods of fracture mechanics. Growth of disbands under cyclic loading is also being studied. Fajlure under compressive loading in presence of a disband is defined in terms of buckling and an elastic stability analysis is utilized for assessing criticality. Analytical predictions are compared with experimental results in both cases.

Keywords
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NONDESTRUCTIVE EVALUATION OF FLAW CRITICALITY IN GRAPHITE-EPOXY LAMINATES

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ABSTRACT

An analytical and experimental study is conducted to determine criticality of interlaminar disbonds by NDE methods. Criticality of such flaws in a shear environment (action of shear near support) is defined in terms of crack propagation and is analyzed by principles and methods of fracture mechanics. Growth of disbonds under cyclic loading is also being studied. Failure under compressive loading in presence of a disbond is defined in terms of buckling and an elastic stability analysis is utilized for assessing criticality. Analytical predictions are compared with experimental results in both cases.

INTRODUCTION

Various kinds of defects can cause relevant strength and stiffness degradation in composite laminates, namely, (i) interlaminar disbonds, (ii) through-the-thickness defects, (iii) defects in bolted and bonded joints, (iv) impact damage, (v) fatigue damage. Different NDI techniques (active and passive), which are usually used for studying effects of such defects, are listed below:

(i) Ultrasonics (modulus degradation measurement and damage detection)
(ii) Accoustic emission (sequential recording of the damage growth process)
(iii) X-ray and thermography (visual and real-time detection of defect growth)
(iv) Structural vibrations (stiffness degradation measurement)
(v) Penetrants
(vi) Holography

This work is mainly directed towards use of ultrasonics for detection and following growth of interlaminar disbonds. Attempts are also being made to use measurements from wave propagation studies for estimating possible modulus degradation due to damages induced by fatigue and moisture conditioning. Analytical studies are aimed at:

(i) definition of required NDI observations,
(ii) model physically realistic damage modes
(iii) assess property degradation, and flaw criticality, and
(iv) translation of results from test systems to real world composite structures.

Mechanical testings are conducted to relate observed state of magnitude and geometry of damage and/or degradation to estimate residual performance capability. Correlations of data from NDI, mechanical tests and analyses are carried out to demonstrate feasibility of using fundamental approach at laminate level for development of quantitative NDE of flaw severity in composites.

CRACK PROPAGATION IN SHEAR ENVIRONMENT

Analytical methodology for stress analysis of a laminated beam containing two symmetrically located disbonds as shown in Figure 1 has been developed. The mixed boundary value problem of anisotropic elasticity has been reduced to the solution of a coupled pair of singular integral equations. This method of reduction has been computerized. For numerical solutions these equations are converted to a discretized system. Evaluation of the unknown functions appearing in these equations yields the stress intensity factors and strain energy release rates. Methods of analysis are based on principles and mathematical techniques commonly used in crack problems of linear elastic homogenous media. Details of the methods are omitted here for brevity, but can be found in [1].

BUCKLING FAILURE UNDER COMPRESSION

Buckling failures under compression near disbonds can be expected in different types of structural configurations. One example is a sandwich construction under flexure with a disbond in the compression flange (Figure 2a). For stability analysis the delaminated compression flange is modeled as a system of four interconnected beams (Figure 2b). Beams 3 and 4 are considered as semi-infinite beams. Beams 2, 3 and 4 are supported on an elastic foundation which can carry extensional and shear loads. The foundation elastic moduli (spring constants) are calculated from the properties of the sandwich construction. All beams are analyzed with laminated beam theory including the effects of shear deformations and prestresses.

A stiffness formulation is employed and the critical value of prestress needed to cause buckling (instability in beam 1 is usually critical) is calculated by solving the resulting eigenvalue problem by a trial and error procedure.

THICK LAMINATE BEAMS WITH IMPLANTED DEFECTS

Graphite-epoxy thick beam laminates with implanted defects of various geometries were fabricated using AS3501-6 prepreg material. The fiber orientation of the 10" long beams was $[(0/90)_6 0_{12}]_S$ and the defect geometries were of square, diamond and "hourglass" shapes. The square defects were fabricated by welding .001" thick teflon film into a tube. The seam in the tube was put in the center of the defect so that the edges of the defect have the same radius of curvature. The diamond and "hourglass" shaped defects were fabricated by shearing two layers of teflon film against an abrasive surface in a manner which causes the two layers of teflon to remain together after shearing. The defects were implanted between the center plies of the laminate at the quarter-span position of the beams.

Ultrasonic C-scans were made of all laminates before and after machining. All beams are precracked prior to testing in order to obtain a sharp crack front. The method used to precrack the beams is to subject the beams to three point bending with clamps placed at the boundaries of the defects. The clamps are used only during the precracking operation to prohibit the defects from propagating completely through the beam. Attempts to precrack the 0.6" rectangular defects and the "hourglass" defects resulted in laminate flexure failure. Attempts to precrack the 1.0" rectangular defects were partially successful. C-scans of these specimens after precracking are shown in Figure 3. Beam No. 12 is the only specimen which exhibited the desired degree of precracking. Figure 4 shows the results of precracking the diamond defect beams. Precracking of these beams occurs at a load of approximately 400 kg as compared with 600 kg for the 1" rectangular defect beams. The results of precracking the diamond defect beams are the most satisfactory. After precracking, three beams with diamond defects and three beams with 1.0" rectangular defects were loaded to failure which occured due to catastropic growth of disbonds. Figure 5 shows a magnified view of the interlaminar defects. Figure 6 depicts the growth pattern of such flaws under cyclic loading [2].

COMPOSITE SANDWICH BEAM WITH IMPLANTED DEFECTS

Test specimens are sandwich beam construction consisting of graphite-epoxy laminate adhesively bonded to an aluminum honeycomb core. The graphite epoxy system is AS-3501-6 GF. Two 23" panels were fabricated in the following configurations, where D denotes the disbond.

$[0/\pm45/\pm45/0/D/0/\mp45/\mp45/0]$;

$[0/+45/+45/0/0/\mp45/D/\mp45/0]$

Disbonds were fabricated from 0.001 inch teflon film. The disbond lengths (L) were 0.5", 1.0", 1.5." Disbond strips were implanted in the laminates on the longitudinal mid-plane at the aforementioned locations in the laminate. The laminates were cured and subjected to ultrasonic C-scan to locate the exact position of the disbonds. Next the laminates were bonded to a 24 lb/ft^3 aluminum honeycomb (Hexel Corp.). American Cyanamid's FM-300/BR 127 sheet adhesive system was the bonding agent. The laminate with the near surface disbonds was oriented so that the disbonds were farthest from the laminate-honeycomb interface. The laminate-adhesive-honeycomb system was cured together in an autoclave. Specimens of 1.0" width and 22.0" length were cut using a rotary diamond saw (figure 7). The beams were instrumented with two strain gages (one on each laminate surface) located at midspan parallel to the beam longitudinal axis. The specimens were tested in a tension-compression load frame employing a four point bending fixture with spans of four and 20" (see Figure 8). A strain rate of .05/ins/in/min was applied to the beams.

The strain from the compressive face of the beam was plotted on the X-axis and tensile strain on the Y-axis using an X-Y recorder. Load levels at which variations from linearity occurred were noted. (Table 1)

The laminates with 0.5" disbonds may have exhibited a catastophic buckling instability. The tensile and compressive strain increased linearly until failure occurred. The 1.0" specimens with disbonds at the laminate mid-plane exhibited the same type of behavior except the buckling of the laminate occurred in a stable manner which was shown by the abrupt change from linear to nonlinear behavior. The specimens with 1.5" mid-plane disbonds exhibited the same gradual nonlinear response from the onset of loading followed by a quasi linear response. The initial compressive strain of the tensile face laminate was due to the initial out of plane deformation due to residual thermal stresses. The 1.5" near surface disbonds were prebuckled to such an extent that the initial tensile strain on the compressive face continued to increase throughout the test. The buckling failure mode is illustrated in a photograph (Figure 9).

CORRELATION STUDIES

Correlation of experimental results for growth of delaminations in precracked $[(0/90)_6 0_{12}]_s$ laminated beams with defects located in mid-plane under static loading is given in table 2. Results from past studies on a different laminate (not precracked) reported in [2] are also shown in this table. The critical values of strain energy release rate from two sets of data reported in table 2 are of the same order and show the same amount of scatter. It appears, therefore, that precracking does not have any significant influence on crack propagation.

Experimental results from honeycomb sandwich beam tests, reported in table 1, are compared in figure 10 with the analytical predictions. The results agree well with one another over a wide range of disbond length.

MODULUS DEGRADATION DUE TO MOISTURE AND FATIGUE DAMAGE

Wave propagation studies on neat resin and $(\pm 45)_{2s}$ coupons are being conducted to measure effects of conditioning on storage and loss moduli. The objective is to determine the possibility of using ultrasonic techniques for assessing magnitude and criticality of damages caused by such conditioning.

Table 1
SANDWICH DISBOND DEFECT STUDY

Sample No.	Defect Size (In.)	Location in Laminate	Buckling Load (Lb.)
1T	1/2	Center	1345
10B	1/2	"	1477
3T	1	"	522
7B	1	"	661
12T	1	"	584
8B	1	"	661
6T	1.5	"	295
5T	1.5	"	309
11T	1.5	"	293
9B	1.5	"	364
3B	1	Near Surface	22
12B	1	"	22
7T	1	"	49
8T	1	"	29

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REFERENCES

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Table 2
ENERGY RELEASE RATES

Laminate	Specimen		G_c (lb/in)
$[(0_4/\pm 45_2/$ $\mp 45_2/0_4)_s]_s$	1-1		5.63
	1-2		6.34
	1-3		2.94
	1-4		3.74
		Avg.	4.66
$[(0/90)_6$ $0_{12}]_s$	1-1		4.37
	1-3		6.53
	1-6		5.02
	D-2		5.23
	D-5		4.14
	D-3		2.93
		Avg.	4.70

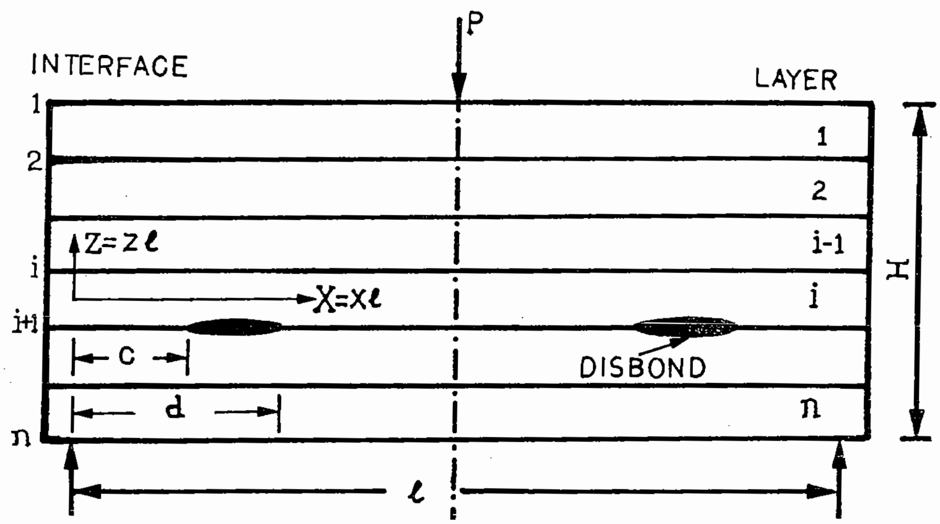

FIG. 1. LAMINATED BEAM CONTAINING DISBONDS

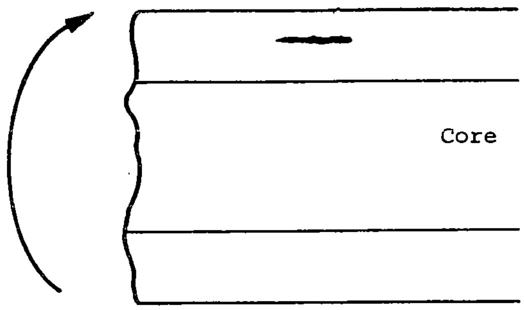

FIG. 2A. SANDWICH BEAM

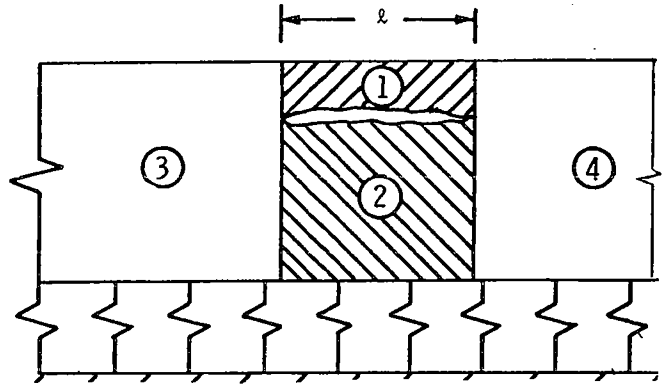

FIG. 2B. INTERCONNECTED BEAM SYSTEM

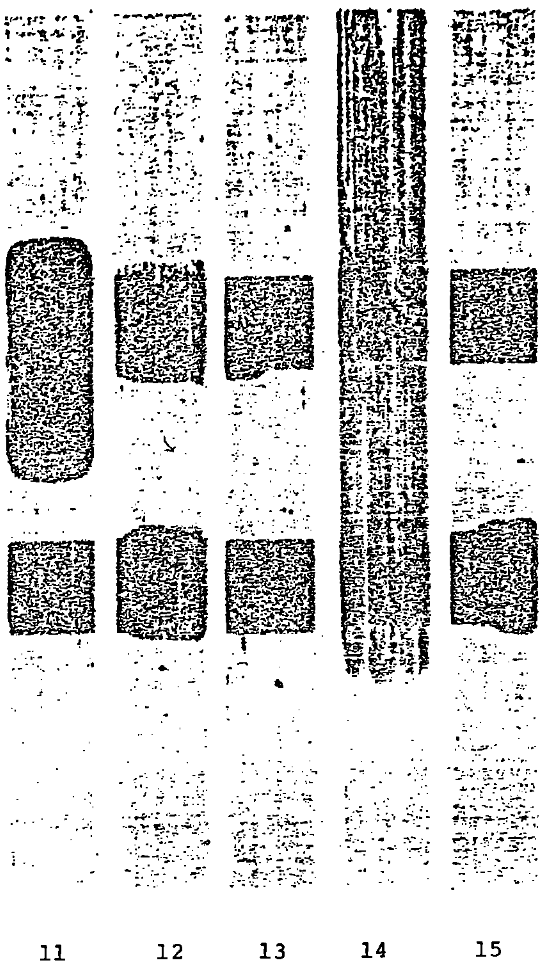

FIG. 3. PRECRACKING SQUARE DEFECTS

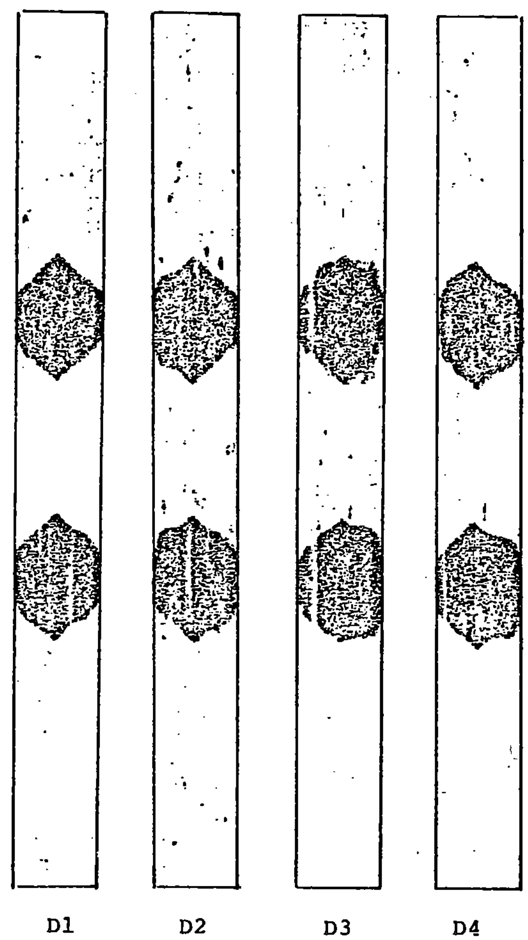

FIG. 4. C SCAN OF DIAMOND DEFECTS

FIG. 5. MAGNIFIED VIEW OF INTERLAMINAR DEFECTS

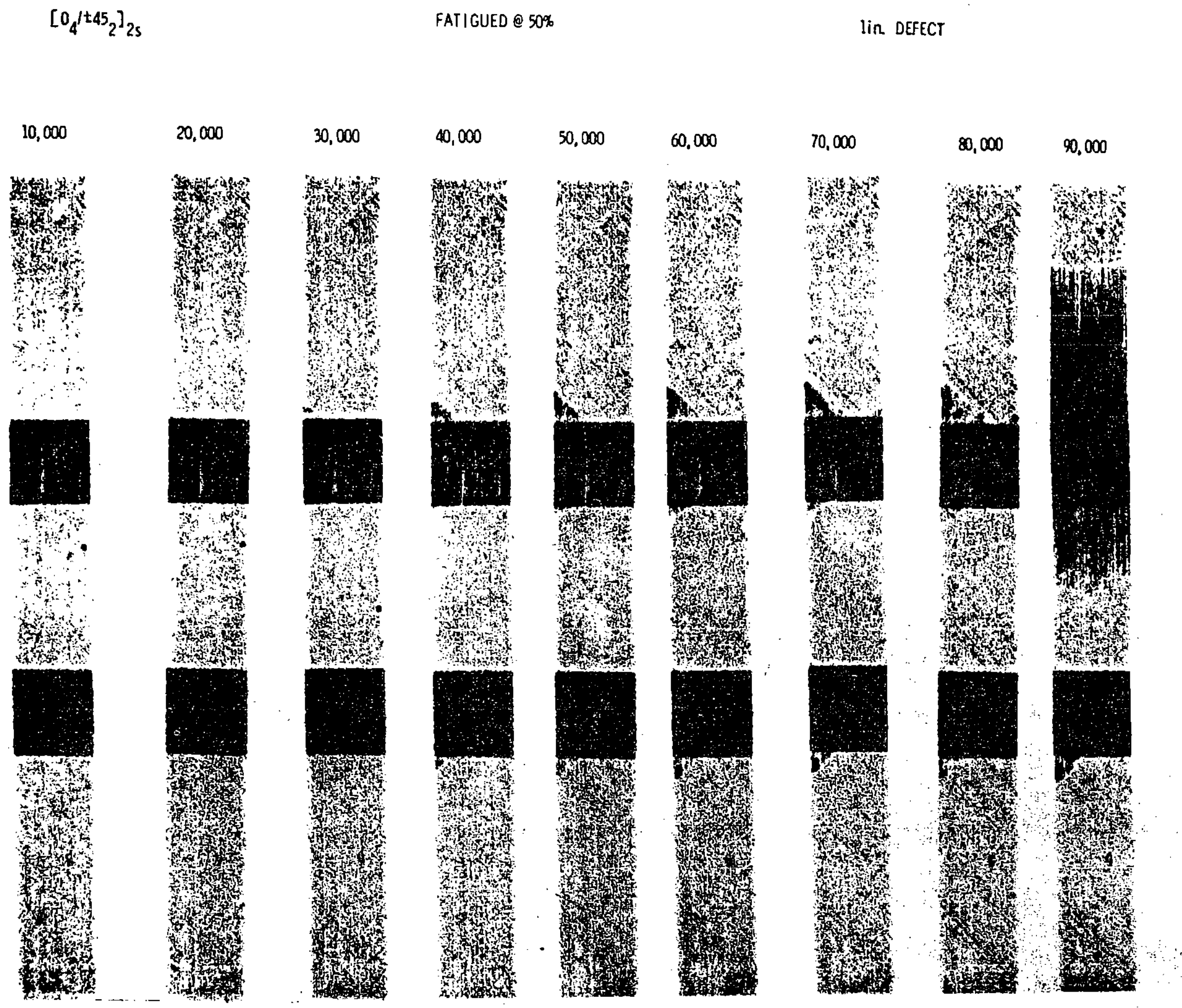

FIG. 6. GROWTH OF DELAMINATION WITH FATIGUE CYCLING

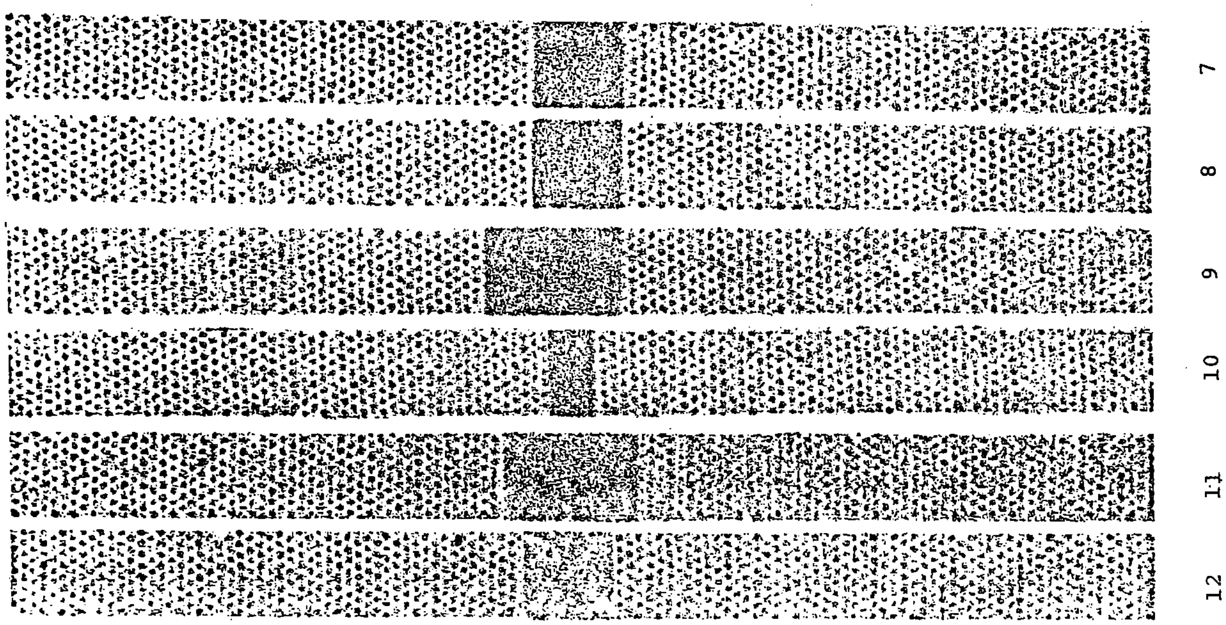

FIG. 7. C SCAN OF SANDWICH BEAM SPECIMENS

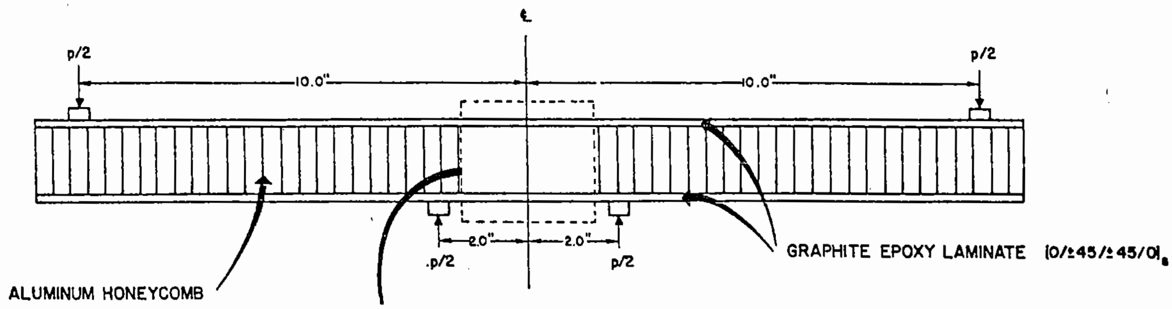

FIG. 8. TEST ON SANDWICH BEAM WITH DISBOND

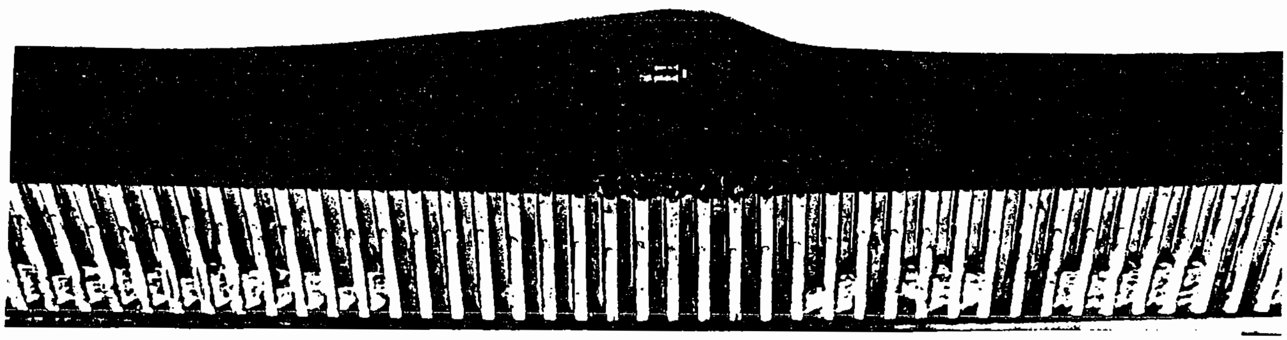

FIG. 9. FAILURE OF COMPRESSION SKIN

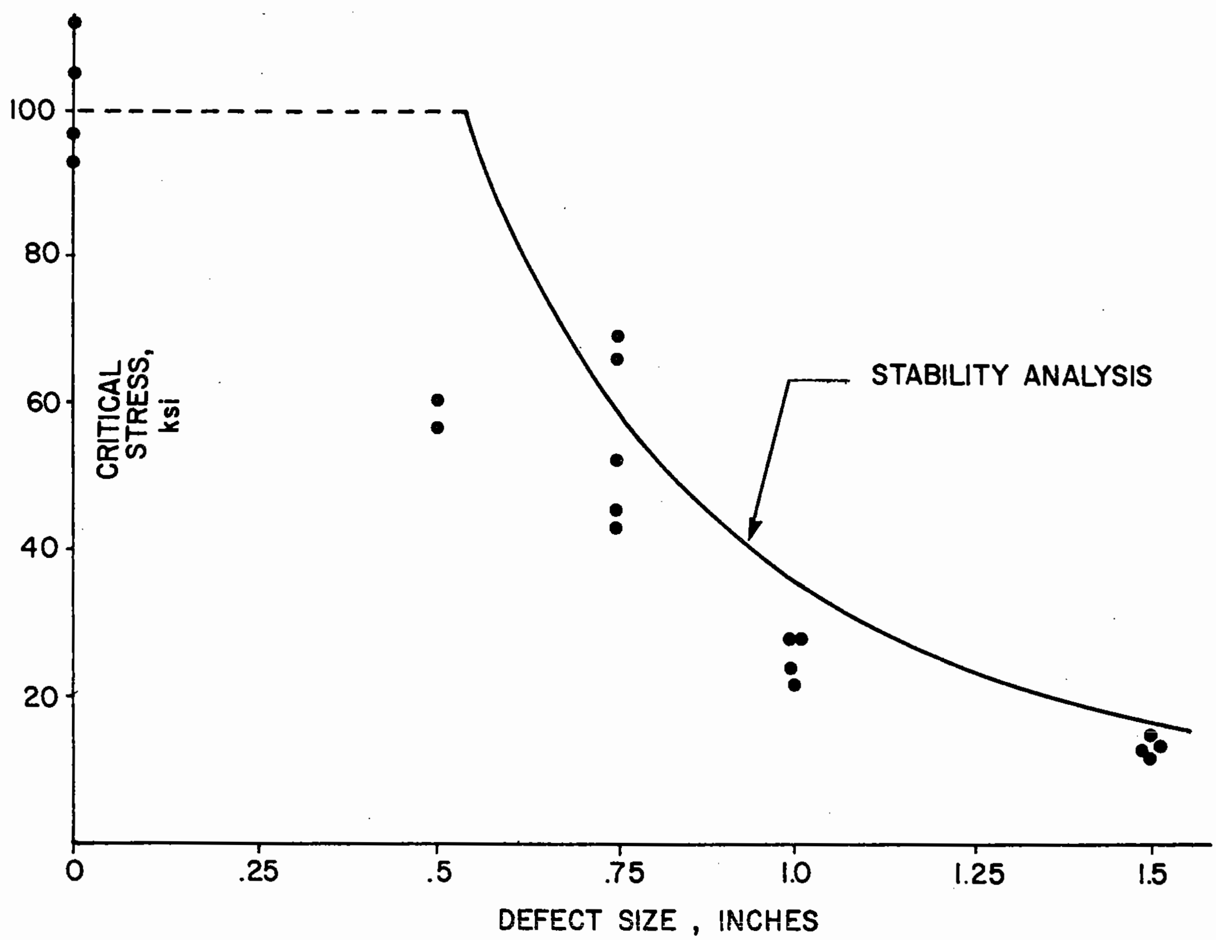

FIG. 10. CRITICAL STRESS VS. DEFECT SIZE